INTRODUCTION TO
Heliophysics SMEX Mission Concept

# Solar Magnetized Atmosphere Research Telescope (SMART)

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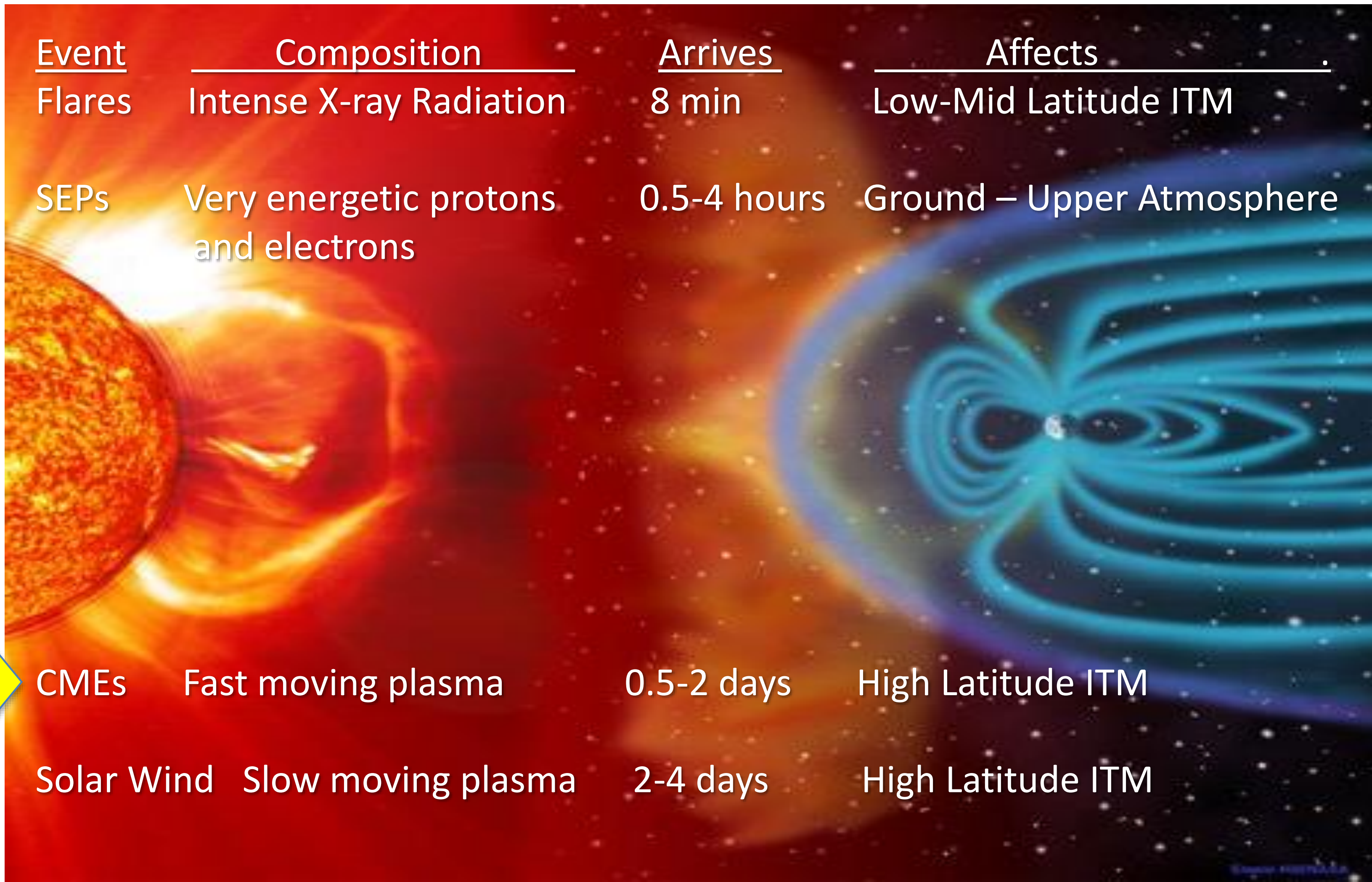
# Science Motivation

- Solar flares, solar energetic particles (SEPs), corona mass ejections (CMEs), and solar wind (SW) are the primary drivers for space weather events at Earth and other planets

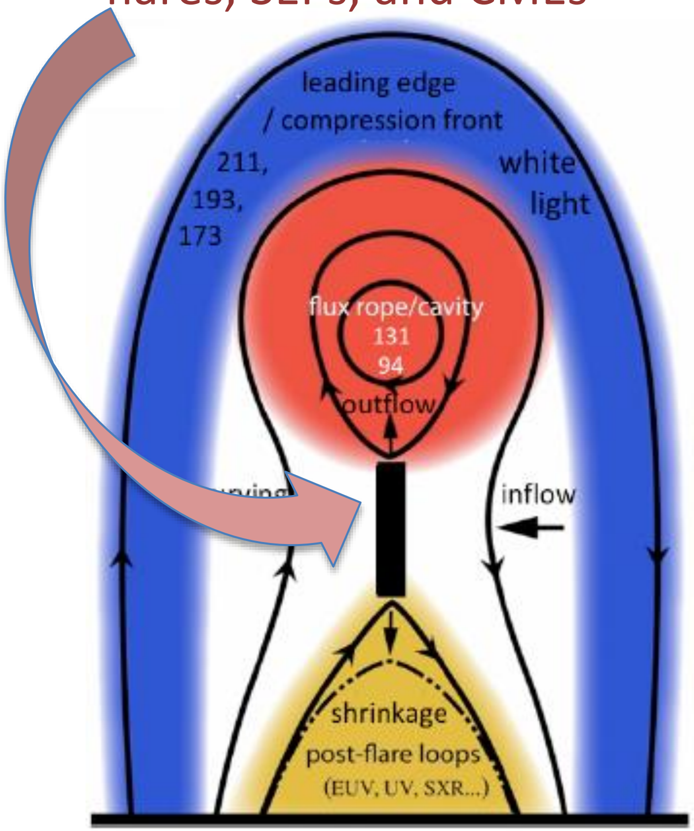


| Event | Composition | Arrives | Affects |
|---|---|---|---|
| Flares | Intense X-ray Radiation | 8 min | Low-Mid Latitude ITM |
| SEPs | Very energetic protons and electrons | 0.5-4 hours | Ground – Upper Atmosphere |
| CMEs | Fast moving plasma | 0.5-2 days | High Latitude ITM |
| Solar Wind | Slow moving plasma | 2-4 days | High Latitude ITM |

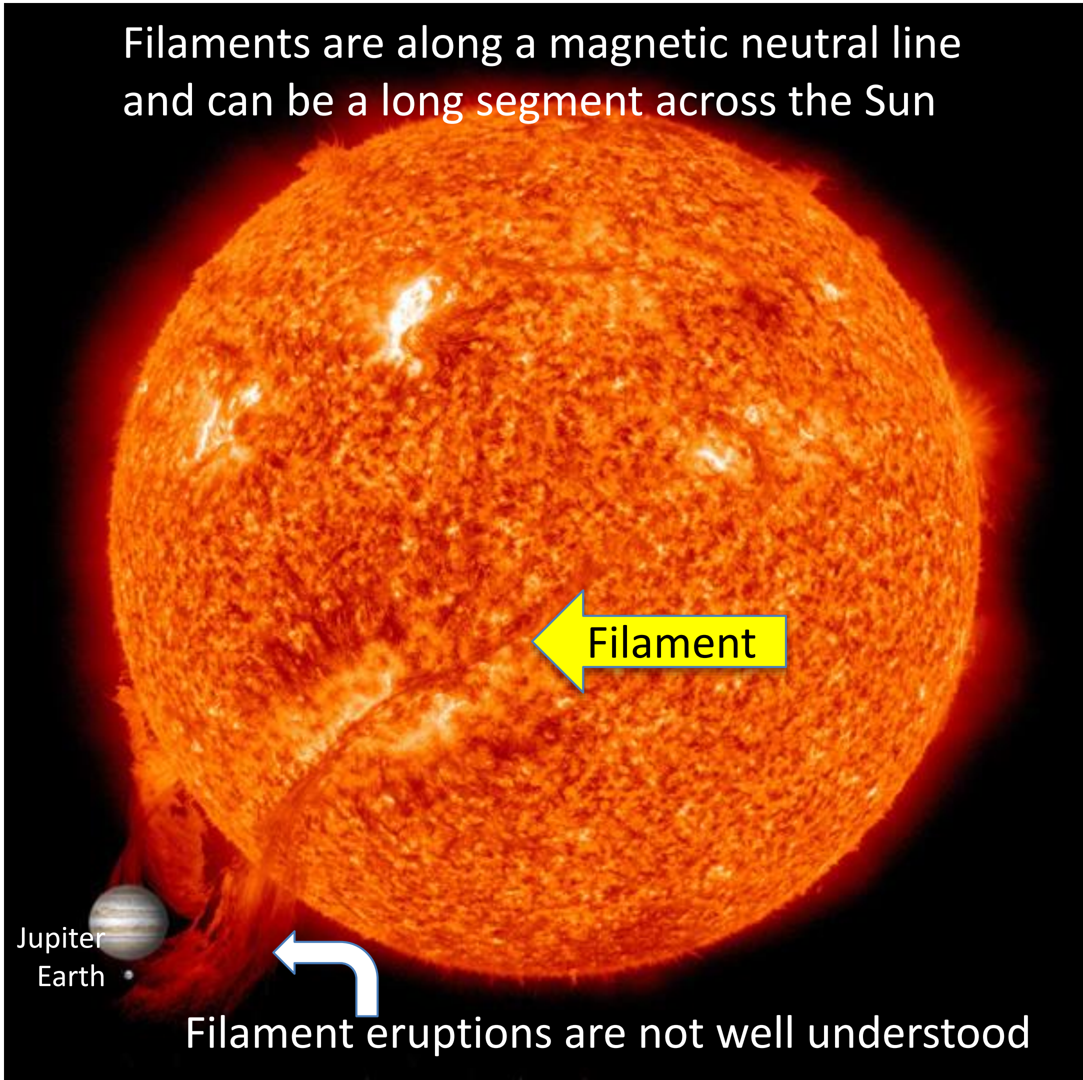
# Science Motivation

- CMEs are primarily released from either coronal magnetic reconnection or filament eruption

Corona magnetic reconnection is well understood to create flares, SEPs, and CMEs

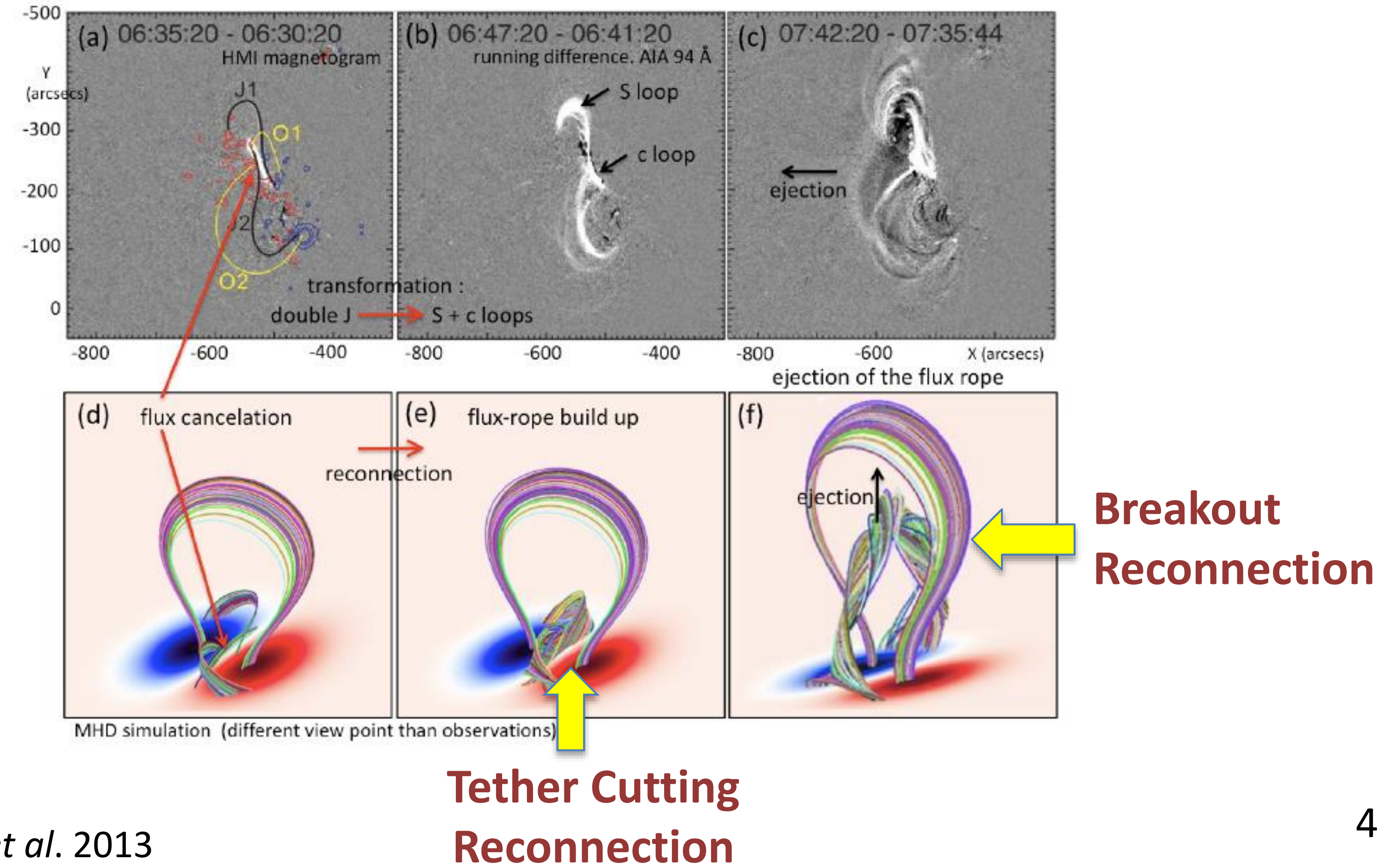



From Schmieder *et al.* 2013



# Science Motivation - Example

- Two different types of magnetic reconnection may be involved during a filament eruption:
  - Tether cutting in twisted, lower flux rope (Moore & Roumeliotis, 1992)
  - Breakout with reconnected upper loops releasing lower flux rope (Antiochos *et al*., 1999)




From Schmieder *et al*. 2013

# Mission Objective and NASA Relevance

- **Our primary mission objective is to determine how magnetic energy emerges, is stored, and released to drive solar filaments and coronal eruptions**

- This objective is directly related to the 2012 NASA Heliophysics Decadal Survey (HP DS) Solar and Heliospheric (SH) objectives:
  - SH 2) Determine how the Sun's magnetism creates its dynamic atmosphere
    - **SH 2b) Determine how magnetic free energy is transmitted from the photosphere to the corona**
  - SH 3) Determine how magnetic energy is stored and explosively released
    - **SH 3a) Determine how the sudden release of magnetic energy enables both flares and coronal mass ejections to accelerate particles to high energies efficiently**

# Mission Objective and NASA Relevance

- [Primary] Determine how magnetic energy emerges, is stored, and released to drive solar filaments and coronal eruptions (HP DS 3a)

- [Primary] Determine how magnetic free energy is transmitted from the photosphere to the corona (HP DS 2b)

- [Primary] Develop advanced methods of forecasting solar eruptive events (HP DS 3d)

- [Secondary] Determine whether chromospheric dynamics is the origin of heat and mass fluxes into the corona and solar wind (HP DS 2a)

- [Secondary] Determine the role of small-scale magnetic fields in driving global-scale irradiance variability and activity in the solar atmosphere (HP DS 1c)

- [Secondary] Discover how the thermal structure of the closed-field corona is determined (HP DS 2c)

# SHP Science Goals

**BOX 10.1 SOLAR AND HELIOSPHERIC PHYSICS PANEL'S MAJOR SCIENCE GOALS AND ASSOCIATED ACTIONS**

**SHP1. Determine how the Sun generates the quasi-cyclical variable magnetic field that extends throughout the heliosphere.**

a. Measure and model the near-surface polar mass flows and magnetic fields that seed variations in the solar cycle.
b. Measure and model the deep mass flows in the convection zone and tachocline that are believed to drive the solar dynamo.
c. Determine the role of small-scale magnetic fields in driving global-scale irradiance variability and activity in the solar atmosphere.

**SHP2. Determine how the Sun's magnetism creates its dynamic atmosphere.**

a. Determine whether chromospheric dynamics is the origin of heat and mass fluxes into the corona and solar wind.
b. Determine how magnetic free energy is transmitted from the photosphere to the corona.
c. Discover how the thermal structure of the closed-field corona is determined.
d. Discover the origin of the solar wind's dynamics and structure.

**SHP3. Determine how magnetic energy is stored and explosively released.**

a. Determine how the sudden release of magnetic energy enables both flares and coronal mass ejections to accelerate particles to high energies efficiently.
b. Identify the locations and mechanisms that operate in impulsive solar energetic-particle sites, and determine whether particle acceleration plays a role in coronal heating.
c. Determine the origin and variability of suprathermal electrons, protons, and heavy ions on timescales of minutes to hours.
d. Develop advanced methods for forecasting and nowcasting of solar eruptive events and space weather.

**SHP4. Discover how the Sun interacts with the local galactic medium and protects Earth.**

a. Determine the spatial-temporal evolution of heliospheric boundaries and their interactions.
b. Discover where and how anomalous cosmic rays are accelerated.
c. Explore the properties of the heliopause and surrounding interstellar medium.

# Synergy with DKIST

- The Daniel K. Inouye Solar Telescope (DKIST) will go on line in 2019.
- Four of the 5 first light instruments are spectropolarimeters that study various spectral lines from the photosphere and corona.
- SMART capabilities covers a region of the solar atmosphere not sampled by DKIST.

# Science Traceability Matrix

| Key | |
|---|---|
| | GREEN = Secondary Objective (option)<br>RED = Measurement is not on SMEX |

| Science Objective | Observational Goals | Scientific Measurement Requirements | | Instrument Functional Requirements | | | Mission Functional Requirements |
|---|---|---|---|---|---|---|---|
| | | Parameter | Requirement | Parameter | Requirement | Comment | |
| Determine how magnetic energy emerges, is stored, and released to drive solar filaments and coronal eruptions<br>(HP DS SH 3a) | Full sun scan (several times daily) to detect flux emergence, monitor magnetic flux changes, and detect eruption signatures. Slow scan for B field, rapid scan for intensity/doppler velocity. | FOV - Full Sun | Raster | Slit length | 1.2 Rsun | Investigating feasibility of long (2.4 Rsun) or short (1.2 Rsun) slit | ISS External Payload<br>Zenith side<br><br>Solar Pointing Platform<br>50% sun view<br>20 arc-sec pointing<br><br>Telescope Steering Mirror<br>0.25 arc-sec pointing<br>1.0 degree range<br><br>On-Board Processing<br>Process 30 Hz images<br>Analyze magnetic fields<br>Lossless data compression<br>Data storage for 1-day<br>Downlink 20-130 Mbps |
| | | Vector Magnetic Field in Chromosphere | < 3 G | Spectral Resolution<br>Meas. Precision<br>Photons / res element<br>Effective area | 100 milliAngstrom<br>0.3%<br>3e6 photons<br>5.4 cm^2 | SMART measures Chomo. fields., field measurements from other atmospheric layers from ground and space based satellites. Photon requirement is based on same error distribution as CLASP 1. EA calculated assumes quiet sun intensity of Mg II k line core and a single slit 1.2 Rsun long. | |
| | | Spatial Resolution for magnetic field | < 3 arc-sec | Plate scale<br>FOV Range<br>Detector Format | 1 arc-sec<br>2.4 R_sun<br>8k x 8k CMOS | Plate scale is assumed to be 1/3 of requirement.<br>Investigating feasibility of long (2.4 Rsun) or short (1.2 Rsun) slit | |
| | | Time to complete raster for magnetic field | < 20 min | Slit number<br>Slit width<br>Raster Step Size<br>Raster Step Rate<br>Polarizer Samples<br>Detector Rate | **1-3**<br>**3 arc-sec**<br>3 arc-sec<br>1 Hz<br>8<br>**8 Hz** | 1 Hz step rate is needed for full-disk raster scan in 20 min with 3 slits.<br>Observation scenario concept:<br>8-Hz detector readout with 1-Hz polarizer filter full rotation provides 8 polarizer angle measurements | |
| | | Time Cadence for Doppler / Intensity | < 2 min | Raster Step Size<br>Raster Step Rate<br>Polarizer Samples<br>Detector Rate | 3 arc-sec<br>5.3 Hz<br>1<br>5.3 Hz | | |
| | High resolution, rapid scan to measure B field, intensity and velocity before, during, and after eruption of filament channel. Slit to be parallel to filament channel. | FOV - Filament Channel | 50 arc-sec raster, slit parallel to filament channel | Slit length | **1.2 Rsun** | Typical filament length | |
| | | Vector Magnetic Field in Chromosphere | < 1 G | Spectral Resolution<br>Meas. Precision<br>Photon/res element<br>Eff Area | 100 milliAngstrom<br>**0.1%**<br>30e6 ph<br>**76 cm^2** | SMART measures Chomo. fields., field measurements from other atmospheric layers from ground and space based satellites | |
| | | Spatial Resolution for magnetic field | < 1 arc-sec | Pixel Resolution<br>FOV Range<br>Detector Format | **0.3 arc-sec**<br>1.4 R_sun<br>8k x 8k CMOS | Pixel scale is assumed to be 1/3 of requirement.<br>8k x 8k CMOS camera provides 0.3 arc-sec/pixel over 1.4 R_sun | |
| | | Time Cadence for Magnetic Fields | < 5 min | Slit number<br>Slit width<br>Raster Step Size<br>Raster Step Rate<br>Polarizer Samples<br>Detector Rate | 1<br>**1 arc-sec**<br>1 arc-sec<br>0.17 Hz<br>48<br>8 Hz | To keep PMU rotation rate the same as full disk mode (8 Hz), we increase the polarization samples. We require additional time at each raster location to achieve required polarization accuracy. | |
| | | Eruption Velocity | < 1 km/sec | Centroid Resolution<br>Spectral Resolution<br>Plate scale | 10 milliAngstrom<br>50 milliAngstrom<br>**25 milliAngstrom** | Doppler & coronal dimming method | |
| | | Eruption Brightness Contrast | **TBD** | **TBD** | **TBD** | Doppler & coronal dimming method | |

# Mission / Instrument Concept

- Primary instrument is a long-slit imaging spectrograph / telescope to measure the magnetic fields of the chromospheric Mg II h and k lines near 280 nm using Hanle (weak field) and Zeeman (strong field) effects
  - NASA MSFC rocket SUMI and MSFC/NOAJ/ISAS CLASP instruments have flown successfully (2010, 2012, 2015) with technology similar to this concept instrument
  - The NASA IRIS SMEX has advanced solar physics by observing the Mg II h and k lines at high spatial and spectral resolution but not with full-disk images.
  - <u>Our mission concept is an advanced study with the capability to measure the chromosphere magnetic field and imaging over the full-disk with 2-20 minute cadence and the flexibility for targeted studies.</u> Our mission focus is on filament eruptions and other global-scale phenomena that IRIS has not addressed.
- Our plan is for sun-sync orbit (SSO) for a 2-year prime mission
  - ~ 10 arc-sec sun pointing by spacecraft and 0.1 arc-sec control for telescope secondary mirror
  - Ka-band downlink (ground station and TDRSS) for ~100 Mbps orbit avg rate

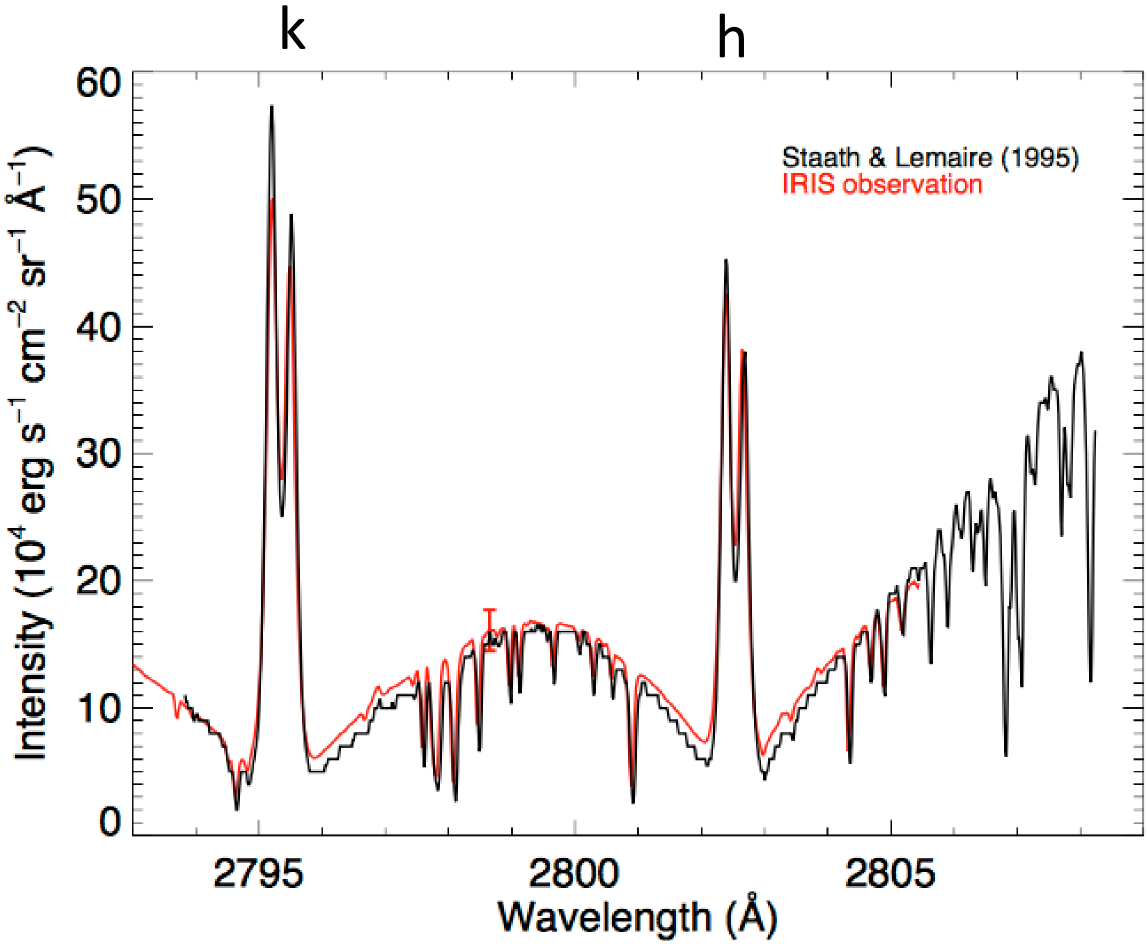
# Current Trades Being Investigated

- Long slit vs short slit
  - Can current design accommodate a long slit to increase full disk cadence? (CLASP 2 has 400 arc sec slit)
- Multiple slits vs single slit
  - Can design be modified to include multiple slits and improve full disk cadence?
- Multiple slit packages vs single slit package
  - Can multiple slits be included to have the option of using a wide slit and improve full disk cadence/polarization accuracy?

# Solar Mg II h & k Lines

- h & k lines are sensitive to magnetic Zeeman effect
  ~1% for 50 G and larger
- k line is sensitive to magnetic Hanle effect (5-100 G)

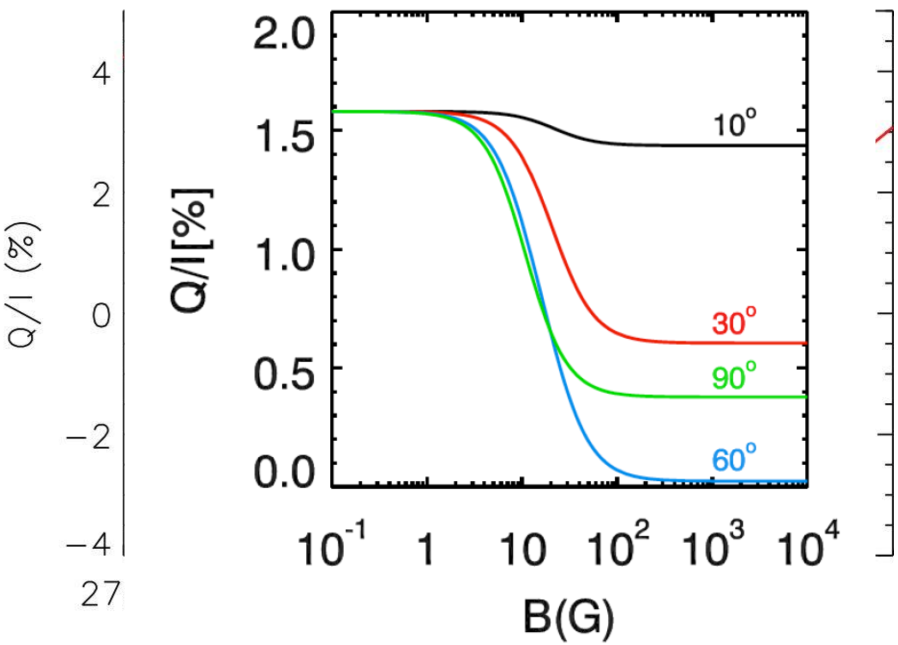
IRIS Measurement

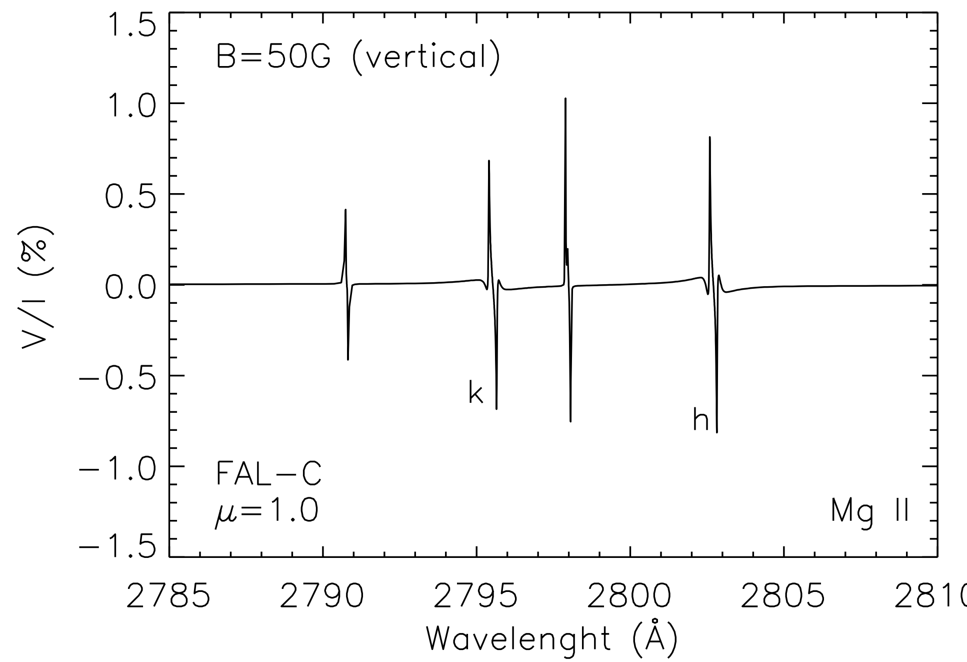


# Solar Mg II h & k Lines

Linear polarization sensitive to scattering polarization and Hanle effect from 5-50 G.

Circular polarization sensitive to Zeeman effect for B > 50 G.

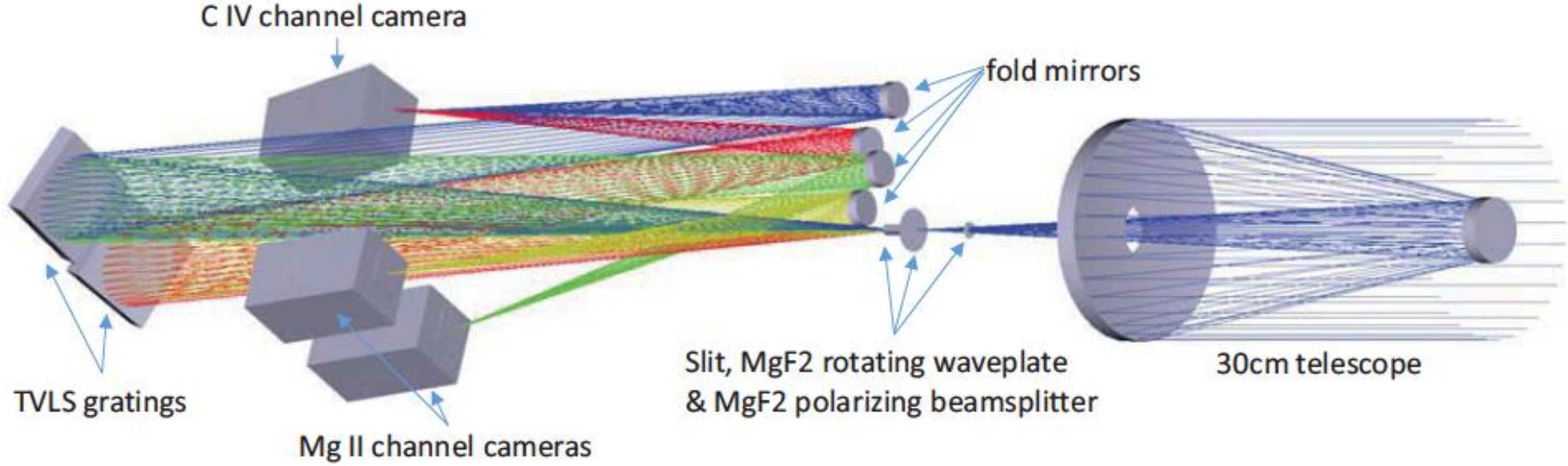


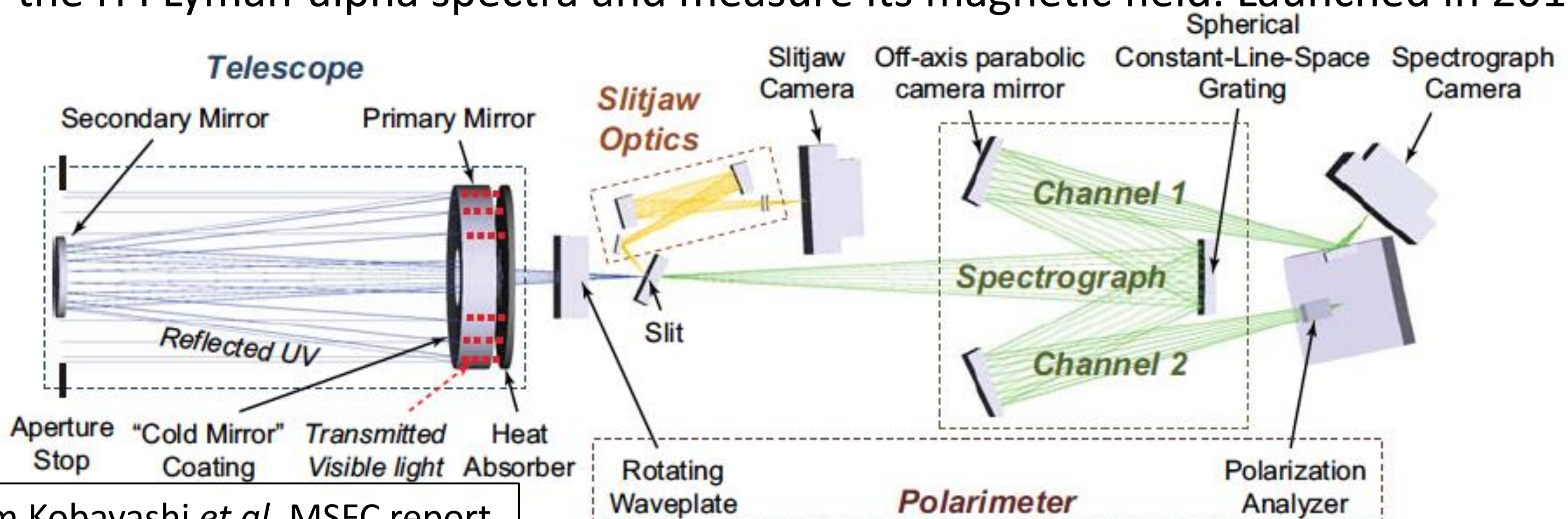

**Belluzzi & Trujillo Bueno (2012; ApJ Letters)**

# NASA MSFC Solar Instruments

- Solar Ultraviolet Magnetograph Instrument (SUMI) is designed to image the Mg II and C IV spectra and measure its magnetic field. Launched in 2010 and 2012.




- Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) is designed to image the H I Lyman-alpha spectra and measure its magnetic field. Launched in 2015.




From Kobayashi *et al*. MSFC report

# NASA MSFC CLASP Instrument Summary

- "SMART" requirement

| Telescope | |
|---|---|
| Type | Cassegrain |
| Aperture | ø277.4 mm |
| Eff. Focal Length | 2614 mm (F/9.42) |
| Primary Mirror | ø290 mm (clear aperture), F/3.54 |
| Secondary Mirror | ø119.4 mm |
| Visible Light Rejection | "Cold Mirror" coating on primary mirror |

| Slit | | |
|---|---|---|
| Slit Width | 18.4 µm (1.45 arcsec) | 1.0 arcsec |
| Slit Length | 5.1 mm (400 arcsec) | 2000 arcsec |

| Slitjaw Imaging System | | |
|---|---|---|
| Wavelength | Lyα (band-pass filter) | ~280 nm |
| Optics | - Fold mirror with multilayer coating<br>- Off-axis parabola x 2<br>- Lyα filter x 2 | |
| Detector | 512 x 512 CCD, 13µm pixel | |
| Plate Scale | 1.03 arcsec / pixel | |
| Resolution | 2.9 arcsec (spot RMS diameter) | |
| FOV | 527 arcsec x 527 arcsec | |

| Polarimeter | |
|---|---|
| Measurements | Stokes I, Q, U |
| Capability | Simultaneous measurement of orthogonal polarizations |
| Optics | - Rotating 1/2 waveplate<br>- Polarization analyzer x 2 |

| Spectrograph | | |
|---|---|---|
| Spectrograph Type | Inverse Wadsworth mounting | |
| Grating Type | Spherical constant-line-space with 3600 $mm^{-1}$ groove density | |
| Grating Size | ø106 mm (clear aperture) | |
| Wavelength | Optimized for Lyα (121.567 nm) | |
| Camera Mirror | Off-axis parabola | |
| Resolution | 0.01 nm (spectral; RMS diamete<br>2.8 arcsec (spatial; RMS diamete | 0.015 nm<br>1.0 arcsec |
| Magnification | 0.73 | |

| Spectrograph Cameras | | |
|---|---|---|
| Detector | 512 x 512 CCD, 13µm pixel | 8k x 8k, 6 um |
| Exposure Time | 0.3 sec (nominal) | 24-30 Hz |
| Plate Scale | 0.0048 nm / pixel (spectral)<br>1.40 arcsec / pixel (spatial) | 0.005 nm<br>0.3 arcsec |
| Field of View | 121.567±0.61 nm (spectral)<br>400 arcsec (along slit) | 13 nm<br>2500 arcsec |

# Mission Budget Estimate

- This is based on $115M cost cap for SMEX.

| PRIMROSE SMEX Budget ROM | | | | | |
|---|---|---|---|---|---|
| Category ($115M cap) | Total | LASP | MSFC | HAO | SAO |
| | ($M) | ($M) | ($M) | ($M) | ($M) |
| -25% Budget Reserve | $ 21.3 | | | | |
| -10% Schedule Margin | $ 8.5 | | | | |
| Working Budget ($M) | $ 85.2 | | | | |
| | | | | | |
| Phase E (2 years)<br>Mission Ops ~$2.0M/yr<br>Data System ~$2.0M/yr<br>4 Science Centers<br>~$1M/center/yr | $ 16.0 | | | | |
| 50% of Phase E for MOC & SOC development | $ 8.0 | MOC | | SOC | |
| HW Phase B-D (4 years) | $ 61.2 | | | | |
| -5% Management | $ 3.1 | | | | |
| -5% System Eng | $ 3.1 | | | | |
| -5% Quality Assurance | $ 3.1 | | | | |
| S/C+Instr Budget ($M) | $ 52.0 | | | | |
| Ball S/C | $ 30.0 | | | | |
| USA Instrument Support | $ 22.0 | CMOS Camera | Integ & Cal | Spectro-polarimeter | Telescope, Steering Mirror |

20% req.
2 wk/yr

| | |
|---|---|
| Instr Cost Model | $92 |
| Japan Contribution | $70 |